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An Assessment of Correlations Between Laboratory and Full-Scale Experiments for the FAA Aircraft Fire Safety Program, Part 2: Rate of Energy Release in Fire

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Washington, DC 20234

July 1982

Sponsored by:

**U.S. Department of Transportation
Federal Aviation Administration**

**Technical Center
Atlantic City Airport, NJ 08405**

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**AN ASSESSMENT OF CORRELATIONS
BETWEEN LABORATORY AND
FULL-SCALE EXPERIMENTS FOR THE
FAA AIRCRAFT FIRE SAFETY PROGRAM,
PART 2: RATE OF ENERGY RELEASE IN
FIRE**

James G. Quintiere

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

1. The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that this is crucial for ensuring the integrity of the financial system and for providing a clear audit trail.

2. The second part of the document outlines the specific procedures for recording transactions. It details the steps involved in the process, from the initial entry to the final review and approval.

3. The third part of the document provides a summary of the key points discussed in the previous sections. It reiterates the importance of accuracy and the need for strict adherence to the established procedures.

4. The fourth part of the document discusses the role of the accounting department in the overall financial management of the organization. It highlights the department's responsibility for ensuring that all financial data is correctly recorded and reported.

5. The fifth part of the document provides a detailed explanation of the various accounting methods used by the organization. It describes how these methods are applied in practice and how they contribute to the overall financial picture.

6. The sixth part of the document discusses the importance of regular audits and reviews. It explains how these processes help to identify any discrepancies or errors and ensure that the financial system is operating as intended.

7. The seventh part of the document provides a conclusion and a summary of the key findings. It reiterates the importance of maintaining accurate records and the need for strict adherence to the established procedures.

8. The eighth part of the document provides a list of references and sources used in the document. It includes a list of books, articles, and other documents that were consulted during the research process.

AN ASSESSMENT OF CORRELATIONS BETWEEN LABORATORY AND
FULL-SCALE EXPERIMENTS FOR THE FAA AIRCRAFT FIRE SAFETY PROGRAM,
PART 2: RATE OF ENERGY RELEASE IN FIRE

by

James G. Quintiere

ABSTRACT

The rate of energy release in fire is discussed. The significance of calorimetric measurements of energy release for materials is related to thermodynamic parameters, namely heat of reaction and stoichiometric coefficients. It is shown that a common set of parameters is necessary to express ignition, flame spread and mass loss due to combustion and heat transfer in fires. The relationship of ignition and flame spread to rate of energy release in fires is presented along with a presentation on upward spread.

Key words: calorimetry, correlations, energy release, flame spread, test methods



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NOMENCLATURE

A	area
B	Spalding mass transfer number
c	specific heat of solid
c_g	specific heat of gas at constant pressure
C	flame spread modulus (Eq. 28)
g	gravitational acceleration
h	heat transfer coefficient
h	enthalpy
h°	enthalpy of formation
H_o	height of window or door
k	thermal conductivity
L	heat of gasification (Eq. 20)
n	exponent of x_p (See Eq. 8)
m	mass
Pr	Prandtl number
q	heat transfer
\dot{Q}	energy release rate
r	mass air to fuel stoichiometric ratio
Re	Reynolds number
t	time
T	temperature
u	velocity
V_f	flame spread velocity
W	width
x	space coordinate
Y_i	mass fraction of i

α	entrainment constant (Eq. 2)
β	flame height coefficient (Eq. 8)
ΔH_v	heat of vaporization
ΔH	heat of reaction
μ	viscosity
ν	kinematic viscosity (μ/ρ)
ρ	density
T	flame spread time (Eq. 106)

Subscripts

a	air
b	burning
e	entrainment
f	fuel
g	gas
o	reference state or opening
ox	oxygen
p	products
py	pyrolysis
s	surface
v	vaporization
w	wall

Superscripts

($\dot{}$)	per unit time
()'	per unit length
()"	per unit area

INTRODUCTION

PURPOSE.

The purpose of this report is to illustrate theoretically the various factors that govern rate of energy release in fires. These factors can be expressed in terms of various parameters and depend on fire phenomena. In a heuristic and qualitative fashion it will be shown that there is a set of parameters or "properties" common to the various phenomena which comprise rate of energy release. The measurement of these parameters would provide the information needed to predict energy release rate with mathematical models. Only through this process will rational scientific correlation emerge between laboratory test data and full-scale fire tests.

BACKGROUND.

The rate of energy release (\dot{Q}) in a fire is the most significant parameter governing fire growth. This can be illustrated by an experimental correlation for predicting the temperature rise (ΔT) in compartment fires given by McCaffrey et al. [1]:

$$\frac{\Delta T}{T_o} = 1.6 \left(\frac{\dot{Q}}{\rho_o c_p T_o \sqrt{g A_o} \sqrt{H_o}} \right)^{2/3} \left(\frac{h_k A_w}{\rho_o c_p \sqrt{g A_o} \sqrt{H_o}} \right)^{-1/3} \quad (1)$$

The other parameters in Eq. (1) relate to property and geometric variables and are given in Ref. [1]. The main point is that ΔT depends on $\dot{Q}^{2/3}$. Temperature is the principle indicator of hazard in terms of human discomfort, burn injury, ignition of other objects and the potential for flashover. Temperature difference is also the promoter of air flow into the fire and \dot{Q} is a manifestation of the rate of fuel consumed and products released from the fire source. Although the quantity of particular products formed depends on the material burning and other factors, the rate of evolution of products and oxygen consumption will be proportional to \dot{Q} . Hence \dot{Q} gives rise to temperature directly and other fire products indirectly, all of which combine to impose a threat to people and property.

The need to measure the energy release rate from combusting materials has led to the development of several apparatuses. Smith [2], Tewarson [3], and Parker [4] are among those who have developed devices to measure the transient rate of energy and other products of combustion from burning materials. These devices are flow-through systems in which measurements in the gas stream flowing from a burning specimen are used to infer the energy and product releases of the material. To put this process in perspective and to demonstrate the relationship of the measured quantities with physical properties will require some analysis. Two issues must be resolved for test method data to have meaning in full-scale fire analyses and correlations. The first issue is the meaning and limitations of the test data collected. Specifically the meaning of energy release rate and its dependence on heat flux, temperature, oxygen, configuration, orientation and scale must be understood. The second issue is to understand the nature of energy release in full-scale fire scenarios and to understand the contributions of ignition and flame spread to that overall process.

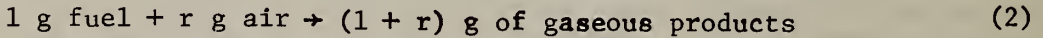
DISCUSSION

IDEALIZED CALORIMETRY.

The meaning of the expression "rate of energy release" in a transient calorimetry apparatus will be considered. An analysis for an idealized solid fuel will show the relationship of energy release rate to thermodynamic properties. Although more realistic fuels may change the details of this analysis, the general form of the results should not vary. The ideal system to be analyzed is typical of devices being used to measure energy release rate. A schematic is shown in Figure 1. The following assumptions are made:

- (1) gas phase transients are negligible, $\frac{d}{dt} = 0$,
- (2) all gas species have identical specific heats, c_g ,
- (3) the combusting fuel is a vaporizing solid with no char yield.

The stoichiometry of the combustion process is given in terms of mass by



Enthalpy relationships for each constituent are given below:

$$\underline{\text{fuel}} \quad h_f = h_f^o + c (T - T_o) , \quad T \leq T_v \text{ (solid phase)} \quad (3)$$

$$h_f = h_f^o + c (T_v - T_o) + \Delta H_v + c_g (T - T_v) , \quad T \geq T_v \text{ (gas phase)} \quad (4)$$

where c_g is the specific heat of the gas,
 c is the specific heat of the solid,
 ΔH_v is the enthalpy difference due to the change from the solid to the vapor phase,
and T_v is the vaporization temperature.

$$\underline{\text{air}} \quad h_a = h_a^o + c_g (T - T_o) \quad (5)$$

$$\underline{\text{products}} \quad h_p = h_p^o + c_g (T - T_o) \quad (6)$$

The heat of combustion, defined as positive for an exothermic reaction, is given by

$$\Delta H = - (1+r) h_p^o + h_f^o + r h_a^o \quad (7)$$

for the solid fuel at the reference state T_o . The ΔH is exactly the quantity that would be measured in an oxygen bomb calorimeter assuming a negligible change in molecular weight of the initial gas state and the final mixture state at T_o . It is also the heat transferred in a flowing system per unit mass of solid burned when the exiting gases have cooled to T_o . This is the intrinsic

property that underlies the energy release rate. For a complex combustion process involving charring and transient conduction losses, the ΔH will vary with time. Nevertheless, a good measurement technique should be capable of recording a transient ΔH consistent with thermodynamic principles. An extension of the following analysis should be able to consider these transient factors.

Conservation laws are applied to the gas enclosed by the dashed boundaries in Figure 1. The inlet and exit states are assumed to be well-mixed and therefore uniform. As assumed, the time rate of change of the gas properties within the volume are negligible.

Mass conservation

$$\dot{m} = \dot{m}_v + \dot{m}_a \quad (8)$$

Fuel specie conservation

$$Y_f \dot{m} - \dot{m}_v = - \dot{m}_b \quad (9)$$

where \dot{m}_v is the gaseous fuel production rate and \dot{m}_b is the burning rate.

Product specie conservation

$$Y_p \dot{m} = (r + 1) \dot{m}_b \quad (10)$$

Air specie conservation

$$Y_a \dot{m} - \dot{m}_a = - r \dot{m}_b \quad (11)$$

or

Oxygen specie conservation

$$Y_{ox} \dot{m} - 0.233 \dot{m}_a = -0.233 r \dot{m}_b \quad (12)$$

Energy conservation

$$\dot{m} h(T) - \dot{m}_a h_a(T_a) - \dot{m}_v h_{f, gas}(T_v) = -\dot{q}_s - \dot{q}_w \quad (13)$$

where $h(T) = Y_f h_f(T) + Y_p h_p(T) + Y_a h_a(T)$,

and \dot{q}_s is the net heat transfer rate to the solid fuel,
 \dot{q}_w^s is the rate of heat transfer lost to the apparatus walls.

By utilizing the enthalpy relationships (2-7) and solving for the specie concentrations at the exit in Eqns. (9-11) the energy equation (13) can be written as

$$(\dot{m}_a + \dot{m}_v) c_g (T - T_o) = \dot{m}_b [\Delta H + c(T_v - T_o) + \Delta H_v] + \dot{m}_{py} c_g (T_v - T_o) - \dot{q}_s - \dot{q}_w \quad (14)$$

Here T_a was taken as T_o , and unburned fuel is allowed to occur at the exit if insufficient air is supplied or if the pyrolysis rate is too great;

$$\dot{m}_{py} = \dot{m}_v - \dot{m}_b \quad (15)$$

is the excess fuel.

A final form of the gas-phase energy equation is developed by considering an energy balance on the solid fuel. For a coordinate system fixed to the regressing solid-gas interface with x taken positive into the solid,

$$\rho c \frac{\partial T}{\partial t} - \dot{m}_v'' c \frac{\partial T}{\partial x} = k \frac{\partial^2 T}{\partial x^2} \quad (16)$$

holds within the solid with $T = T_v$ at $x = 0$ and $T = T_o$ as $x \rightarrow \infty$. At the vaporizing interface

$$\dot{q}_s'' + k \frac{\partial T}{\partial x} \Big|_{x=0} = \dot{m}_v'' \Delta H_v \quad (17)$$

holds for solid and gas flowing across the interface with flow rate per unit area \dot{m}_v'' and at the temperature T_v . The restriction that steady state holds in the solid, i.e. $T=T(x)$ only, leads to

$$T = (T_v - T_o) e^{-\frac{c \dot{m}_v''}{k} x} + T_o \quad (18)$$

and

$$\dot{q}_s = \dot{m}_v [\Delta H_v + c (T_v - T_o)]. \quad (19)$$

If transient conduction were considered it is apparent that time-dependent terms would occur in Eqns (18) and (19). The effective heat of gasification, L , is a useful fire parameter defined as

$$L = \frac{\dot{q}_s}{\dot{m}_v} \quad (20)$$

and for this example,

$$L = \Delta H_v + c (T_v - T_o). \quad (21)$$

In general L would depend on time due to any transient effects in the solid.

Eq (19) is substituted in Eq. (14) to yield

$$(\dot{m}_a + \dot{m}_v) c_g (T - T_o) = \dot{m}_b \Delta H - \dot{m}_{py} \left[\Delta H_v + (c - c_g) (T_v - T_o) \right] - \dot{q}_w \quad (22)$$

As stated earlier if the exit gases are cooled to T_o , and if $\dot{m}_{py} = 0$, the rate of heat lost is

$$\dot{q}_w \Big|_{\substack{T=T_o \\ \dot{m}_{py}=0}} = \dot{m}_b \Delta H \quad (23)$$

Hence all of the energy released by the chemical reaction is manifested as a heat loss. This clearly shows the significance of $\dot{m}_b \Delta H$ as the energy release rate for the combustion process. Although this analysis assumed lack of transients in the gas and solid phases, the equations apply at any instant of time and changes in the nature of the gas-phase reaction are still allowable. For example, the chemical composition of the gaseous fuel can change as the burning process proceeds in time. This would reflect changes in the values of the stoichiometric ratio, r , and the enthalpies of formation, h_f^o and h_p^o . Hence ΔH could change with time.

The utility of ΔH is clear but its measurement needs some discussion. The measured "rate of energy release" (\dot{Q}) must be shown to be $\dot{m}_b \Delta H$. A thermal method to measure energy release must not only measure the exit temperature or energy flow rate through the apparatus but it must also eliminate or account for the heat losses to the walls. For $\dot{m}_{py} = 0$, i.e. sufficient air for combustion,

$$\dot{Q} = \dot{m}_b \Delta H = (\dot{m}_a + \dot{m}_v) c_g (T - T_o) + \dot{q}_w \quad (24)$$

The terms on the right-side of Eq. (24) must all be known to give an accurate measurement for \dot{Q} or ΔH . The difficulty to account for the heat losses to the surroundings under transient conditions is a disadvantage of the thermal method.

An alternative method to determine \dot{Q} is to utilize the empirical result that the heat of combustion per unit mass of oxygen reacted (ΔH_{ox}) is nearly a constant for most materials. This has been demonstrated by Huggett [5]. In terms of the present example it follows for Eq. (12) that

$$\Delta H = 0.233r \Delta H_{ox} \quad (25)$$

The stoichiometric ratio, r , can be determined from Eq. (12) by measurements of mass flow rates, mass loss rate of the fuel and oxygen concentration at the exit provided sufficient air is supplied for combustion. Hence both ΔH and r are found without any thermal measurements. A nominally constant value for ΔH_{ox} is 13 kJ/gO₂.

THE ROLE OF FIRE PARAMETERS.

The parameters ΔH , r and L are of fundamental importance in arriving at the overall energy release rate in full-scale fires. The dependence of these parameters on environmental conditions and effects of size, orientation and configuration must be known. The data of Tewarson [3] suggest that variations in ambient oxygen concentration and external radiant heat flux lead to little variation in ΔH for a given material. Ultimately, these parameters must be clearly demonstrated to represent material properties in the main, and weakly dependent on the fire conditions and processes. If that can be shown, they will have great utility.

More data and analysis are required to fully establish whether these parameters are complete and sufficiently fundamental. If they depend strongly on many factors, then their utility is diminished. Since most predictive analytical relationships in fire require a knowledge of these and other similar property parameters, a theoretical basis for understanding the performance of real materials in fire may not then be possible. Reliance of material evaluation would be purely empirical. Alternatively the establishment of a general property basis, consistent with current theoretical methods, offers the means of predicting and correlating results in full-scale scenarios.

FLAME SPREAD EXAMPLE. The steps necessary to understand the release of energy in fire will be illustrated. This process will demonstrate the role of the parameters introduced above and the various influencing factors. A one-dimensional flame spread process will be considered for a material of width, W . An external radiant flux distribution will be imposed on the material at a sufficient initial value to cause piloted ignition. The example is illustrated in Figure 2. The material will be assumed to be thick so that burn-out will not be considered. In general, the prediction of extinction and its dependence on other variables must be considered to fully describe the process.

The energy release rate is given by

$$\dot{Q} = W \int_0^{x_f} \dot{m}_b'' \Delta H dx \quad (26)$$

where \dot{m}_b depends on time and position. The material will ignite in time t_{ig} corresponding to $\dot{q}''(0)$ and spread to the minimum flux required for piloted ignition, $\dot{q}_{o,ig}''$, shortly thereafter. That transit time will be considered negligible. Flame will now spread (at a relatively slow rate provided this occurs on a "floor" or laterally on a "wall") between x_o and x_e . At x_e the minimum flux for spread, $\dot{q}_{o,s}''$, will be encountered and the spread will cease. The position of the flame front is given by

$$x_f - x_o = \int_{t_{ig}}^t v_f dt \quad (27)$$

where

$$v_f = C / \left[\dot{q}_{o,ig}'' - \dot{q}_e''(x) \right]^2 \quad (28)$$

at most. The flame spread parameter C can be found from theory or experiment along with the limiting heat fluxes [6]. The pyrolysis rate is given by

$$\dot{m}_v'' = \frac{\dot{q}_f'' + \dot{q}_e'' - \dot{q}_s''}{L} \quad (29)$$

where \dot{q}_f'' is the flame heat flux,
and \dot{q}_s'' is the surface radiative loss.

The flame flux is not generally predictable for realistic fire conditions since it depends on scale, orientation, ambient conditions and similar variables. In principle it can be predicted; however, progress has been limited to simple materials and configurations.

In order to simplify the results for this example assume that \dot{q}_f'' is a constant and that $\dot{q}_{e,1}$ and $\dot{q}_{e,2}$ represent mean values in the ignition and spread zones. Also assume $\dot{m}_v'' \approx \dot{m}_b''$ or sufficient air is available.

$$\dot{Q} = W \left(\dot{q}_f'' - \dot{q}_s'' + \dot{q}_{e,1}'' \right) \left(\frac{\Delta H}{L} \right) x_o + W \left(\dot{q}_f'' - \dot{q}_s'' + \dot{q}_{e,2}'' \right) \left(\frac{\Delta H}{L} \right) \frac{C (t - t_{ig})}{(\dot{q}_{o,ig}'' - \dot{q}_{e,2}'')}^2 \quad (30)$$

for $t_{ig} \leq t \leq t_e$ when $x_f = x_e$.

If the process were to become air limited then

$$\dot{Q} = \left(\frac{\dot{m}_a}{r} \right) \Delta H \quad (31)$$

where \dot{m}_a is the rate of air flow to the fire.

This relatively simple result shows the various factors controlling the evolution of energy in a fire. There will be ignition after sometime over a region defined by $\dot{q}_{o,ig}''$, a characteristic of the material for the most part [6]. Subsequently, flame will spread depending on time and other factors (eg. C). The roles of the "property" parameters: ΔH , L and r are clearly shown. Finally the extent of spread will be limited by the minimum external flux needed to sustain spread $\dot{q}_{o,s}''$. The significant effects of all the other variables have been contained in \dot{q}_f'' . Questions of the invariance of parameters like ΔH still remain, but the structure of the example is still valid. The variation of \dot{Q} in time is also shown in Figure 2. Of course, in a more realistic case, burn-out will occur, and the resulting curve would give smaller values for \dot{Q} with decay to zero eventually.

The maximum value for \dot{Q} from Eq. (30) can be written as follows:

$$\dot{Q} = W \left(\dot{q}_f'' - \dot{q}_s'' + \dot{q}_{e,1}'' \right) \left(\frac{\Delta H}{L} \right) x_o + W \left(\dot{q}_f'' - \dot{q}_s'' + \dot{q}_{e,2}'' \right) \left(\frac{\Delta H}{L} \right) (x_e - x_o) \quad (32)$$

The first term results after ignition, and the second term represents the flame spread process up to the extinction position x_e . For a given material and external heat flux distribution, these distances (x_o, x_e) can be determined provided the parameter $\dot{q}_{o,ig}''$ and $\dot{q}_{o,s}''$ are known. Figure 3 displays initial

distributions imposed on a specimen in the ASTM E-84 Steiner tunnel test and on a specimen in the Bunsen Burner test method. If a value of $\dot{q}_{o,ig}'' = 2 \text{ W/cm}^2$ is considered, then ignition would occur over 1.5 m in the tunnel and over 5 cm in the Bunsen Burner test. Eq. (32) would suggest that the energy release rate per unit width (\dot{Q}/W) would therefore be 30 times greater in the tunnel test. If the material has a minimum flame spread heat flux of 0.5 W/cm^2 , flame propagation will occur for considerable distance in both tests. This discussion only serves as an illustration in understanding the effect of initial heat flux conditions. It applies to test methods and full-scale fire simulations. For the tests in this discussion, the vertical orientation in a Bunsen Burner test or the wind-driven ceiling spread in the tunnel would add complexities not considered. The forward heat transfer in both cases would result from flames extending far beyond the initial ignition zone (x_o) and in fact would contribute additional heating to \dot{q}_e'' . The resulting spread velocity would depend on x_o and this flame heating distance. A general solution to this problem does not yet exist, and the differences in scale in the two tests do not alone constitute a basis for differences in flame spread that might be observed. Nevertheless a simple model will be described for upward flame spread in order to illustrate the variables on which this type of flame spread depends.

FLAME SPREAD ON A VERTICAL SURFACE. The model considered is based on concepts involving a prediction of flame height (x_f) in terms of pyrolysis length (x_p) based on entrainment, Spalding's treatment for predicting burning rate, and a flame spread model based on conduction in an inert solid. The analysis follows:

Flame height is determined by equating air required for combustion with air supplied. For r , the effective mass stoichiometric air-fuel ratio, the air supplied is

$$\dot{m}'_a = r \dot{m}'_f \quad (33)$$

where \dot{m}'_f is the fuel produced per unit time per unit width. The mechanism for air flow into the boundary layer is considered to be by entrainment with the entrained velocity

$$u_e = \alpha u \quad (34)$$

where α is the entrainment constant and u is a characteristic velocity in the boundary layer. The characteristic velocity follows from a momentum balance neglecting the wall shear stress and treating the flame zone at a uniform flame temperature T_f .

$$u = \sqrt{2 (1 - T_a/T_f) g x} \quad (35)$$

Then

$$\dot{m}'_a = \int_0^{x_f} \rho_a u_e dx$$

or

$$\dot{m}'_a = \frac{2}{3} \alpha \rho_a \sqrt{2 (1 - T_a/T_f)} g x_f^{3/2} \quad (36)$$

The fuel production rate is assumed to be governed by the convective heat transfer process alone. The effect of flame radiation or external radiation must be eventually added for completeness. From simple mass transfer principles [7]

$$\dot{m}''_f = \frac{h}{c_p} \ln(1 + B) \quad (37)$$

where B is the Spalding mass transfer number and h will be based on turbulent boundary layer flow with u (Eq. (35)) as the characteristic velocity.

$$h = 0.0292 \frac{k}{x} Re_x^{4/5} Pr^{1/3}$$

or

$$h = 0.0292 \frac{k}{v^{4/5}} \frac{2}{x} \frac{1 - T_a/T_f}{g} Re_x^{2/5} Pr^{1/3} x^{1/5} \quad (38)$$

Then

$$\dot{m}'_f = \int_0^{x_p} \dot{m}''_f dx \quad (39)$$

Substituting appropriately into Eq. (33) and solving for x_f gives

$$x_f = \beta x_p^{4/5} \quad (40)$$

where

$$\beta = \left(\frac{(0.0292)(6/5)(3/2)r}{\alpha} \right)^{2/3} \left(\frac{\mu}{\rho_a} \right)^{2/15} \left(\frac{2g(1-T_a/T_f)}{Pr} \right)^{1/15} \ln(1+B)^{2/3}$$

For polymethylmethacrylate (PMMA), $B = 1.4$ and $r = 8$; also taking $\alpha = 0.1$, $\rho_a = 1.2 \text{ kg/m}^3$, $\nu = 20 \times 10^{-6} \text{ m}^2/\text{s}$, $Pr = 0.7$ and $1 - T_a/T_f = 0.75$ yields

$$\beta = 1.67 \text{ cm}^{1/5}$$

If r were taken at four times stoichiometric then $\beta = 4.3 \text{ cm}^{1/5}$. The inclusion of flame radiation would also increase β . Orloff, deRis and Markstein [8] derive from PMMA flame spread experiments

$$x_f = 5.3 x_p^{0.78} \text{ (in cm units)} \quad (41)$$

The results of this simple analysis are in remarkable agreement.

The flame spread rate is determined by Eq. (40) and the results from

Orloff et al. [8] that

$$\frac{dx_p}{dt} = \frac{x_p}{T} \frac{\ln n}{n-1} \ln \left(\frac{x_f}{x_p} \right) \quad (42a)$$

where $n = 4/5$ and the transit time between x_p and x_f is

$$T = \frac{\pi}{4} (k\rho c)_s (T_p - T_s)^2 / (\dot{q}_f'')^2 \quad (42b)$$

where $k\rho c$ is the thermal inertia of the solid, T_p in its pyrolysis or ignition temperature and \dot{q}_f'' as from Eq. (37) is

$$\dot{q}_f'' = \dot{m}_f'' L = \left(\frac{L}{c_p} \right)^{\ln(1+B)} \cdot h(x_p) \quad (43)$$

Substituting into Eq. (42) yields

$$\frac{dx_p}{dt} = f \cdot x_p^{3/5} \ln(\beta/x_p^{1/5}) \quad (44)$$

where f depends on the properties of the solid fuel: $k\rho c$, ΔH , r , L , T_p and other less variant quantities. In a complete model, radiation parameters would also appear. Ignoring the dependence in the logarithmic term, the pyrolysis front grows as

$$x_p \sim t^{5/2} \quad (45)$$

and $\frac{dx_p}{dt} \sim t^{3/2}$. Hence the spread rate increases with time and clearly depends on scale or the extent of growth of the front (i.e. the pyrolysis length)

A simpler example will be used to illustrate the effect of a fixed flame source as an ignition source and continuing source of heat. This is based on an idea by Parker [9] to explain the ASTM E-84 tunnel test behavior. Consider $n = 1$ and flame lengths are additive with x_o the flame length of the igniting source. Also assume instant ignition so that at $t=0$, $x_p = x_o$. In place of Eq. (42) approximate

$$\frac{dx_p}{dt} \sim \frac{x_f - x_p}{T}, \quad (46)$$

where T or \dot{q}_f'' is considered independent of t . The solution is

$$x_p = x_o \left(\frac{\beta \exp\left(\frac{\beta-1}{T}\right) t - 1}{\beta-1} \right) \quad (47)$$

and

$$\frac{dx_p}{dt} = \frac{x_o \beta}{T} \exp\left(\frac{\beta-1}{T}\right) t \quad (48)$$

The results clearly depend on scale and on the length of the igniting flame. The quantity β increases with B and in general can be considered proportional to the ratio of energy release per energy required for burning. For large β , flame spread by Eq. (47) is indefinite. For small $\beta < 1$, the spread reaches a limit of $x_o/(1-\beta)$. In small scale tests the minimal effects of flame radiation could result in $\beta < 1$, but for the same material tested in a larger scale, β could effectively be larger than 1. Another view of β stems from considering that most materials will not burn unless an external radiant source supplies energy. Hence the burning rate expression may be represented by

$$\dot{m}_f'' = \dot{m}_o'' + \frac{\dot{q}_e''}{L} \quad (49)$$

where the second term represents the external flux contribution to mass loss rate, and \dot{m}_o'' is the burning rate at zero external flux. For many materials \dot{m}_o'' is negative, implying burning takes place above some critical heat flux. Using similar arguments to arrive at x_f as before, but replacing Eq. (37) with Eq. (49), yields that

$$x_f = \beta x_p^{2/3}$$

where β now is proportional to $(\dot{m}_o'' + \frac{\dot{q}_e''}{L})^{2/3}$.

For ease in illustration, consider the $2/3$ power to be approximately 1. Then from Eq. (47) it is clear that flame spread will stop or grow exponentially depending on the value of $\dot{m}_o'' + \dot{q}_e''/L$, i.e. flames will not propagate if this value is small enough. Hence, especially for materials that do not sustain burning without external heating, \dot{q}_e'' must be large enough to promote continued spread.

CONCLUSIONS

This analysis has attempted to illuminate the processes that relate to energy release in fire growth. Heuristic models have been presented for some of these processes in order to show the significant variables that govern them. Techniques for measuring rate of energy release using calorimetry devices only make measurements for a fixed sample size. The interpretation of these measurements into an effective heat of combustion property has been shown. Also the pitfalls of measuring rate of energy release by thermal techniques have been discussed. The oxygen consumption technique offers a more accurate approach. In fire growth the total energy release process will depend on more than just calorimetry data since the processes of ignition, flame spread and extinction play a role. Although complete models for predicting these processes have not been developed, it is clear that a set of parameters is common to current models. The analyses presented have illustrated these variables. More complete solutions involving flame radiation effects will add some additional parameters. The list of relevant parameters follows:

1. Heat of reaction, ΔH .
2. Stoichiometric air to fuel ratio, r .
3. Heat of vaporization, L .
4. "Creeping" flame spread coefficient, C .
5. Minimum radiant flux for ignition, $\dot{q}_{o,ig}''$.
6. Minimum radiant flux for flame spread, $\dot{q}_{o,s}''$.
7. Thermal inertia, $k\rho c$.

There are likely to be additional parameters related to fire growth as models become more complete and specific. Also some of these parameters are dependent on time and environmental conditions so that their most appropriate representation needs to be decided. Nevertheless they are measurable for many materials as demonstrated by the work of Tewarson [3] and Quintiere [6]. It should be emphasized that the intended application of these parameters is equivalent to, but hopefully more general than, simply measuring energy release rate per unit area [2]. In any case any attempt to short-cut correlation analyses between test method data and large fires by ignoring important features of a particular fire scenario will not be successful. For example, a comparison of energy release data from a calorimetry device with temperatures in full-scale fires without concerns for flame spread could be deficient.

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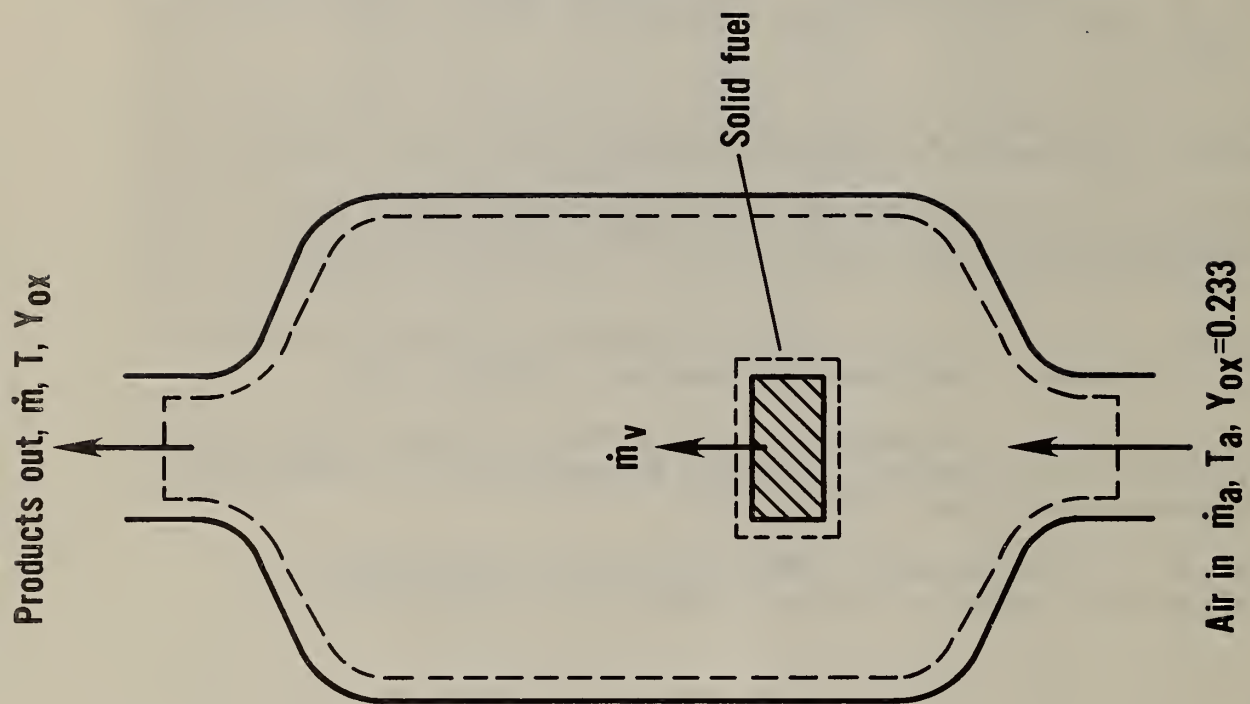


Figure 1 - An Idealized Calorimeter

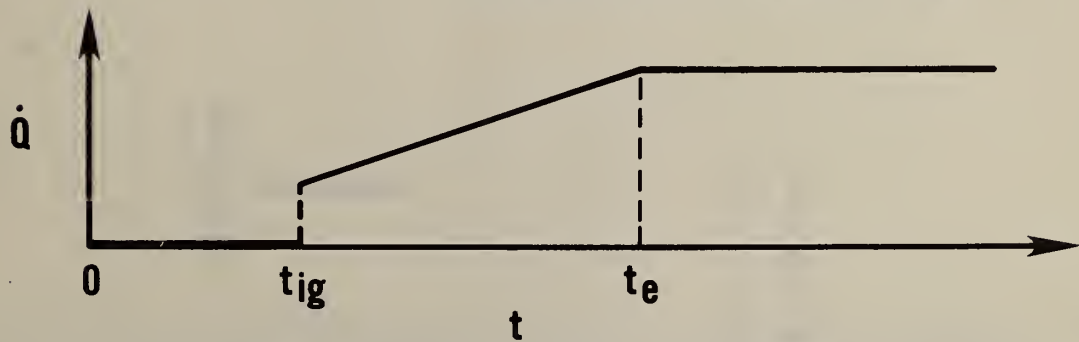
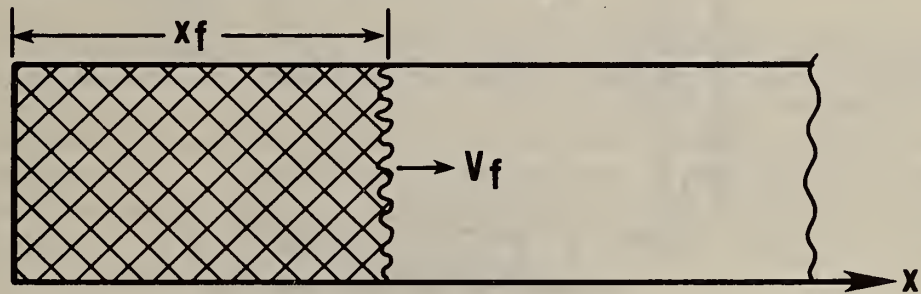
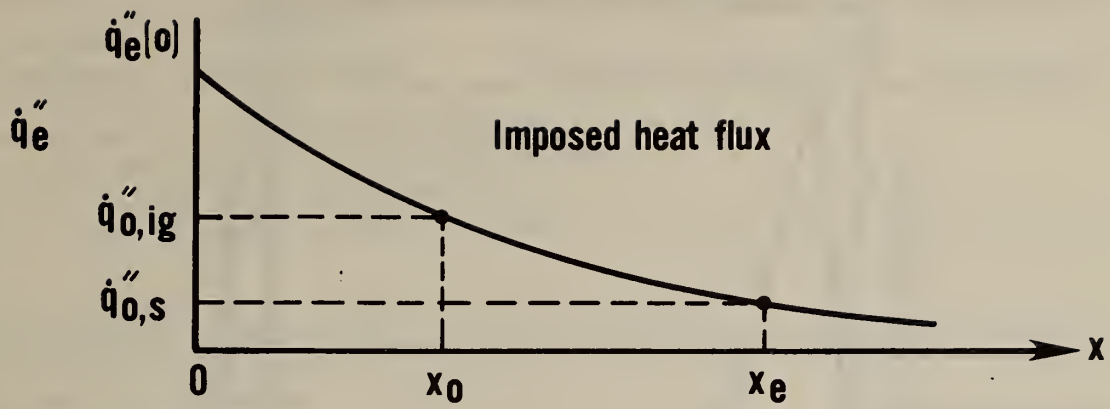


Figure 2 - Flame Spread Example

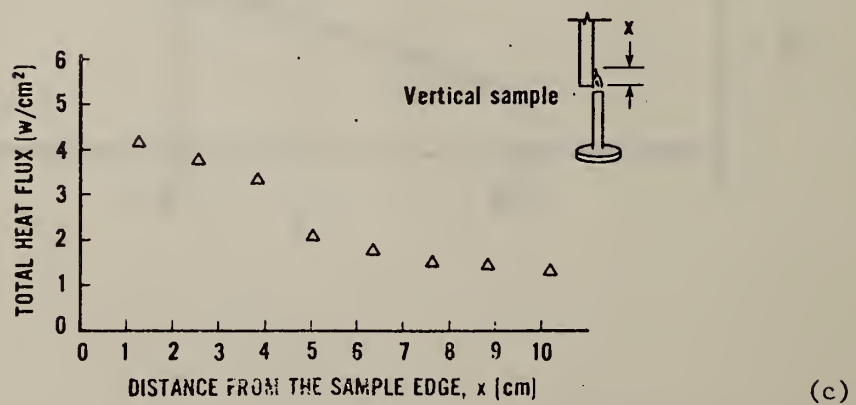
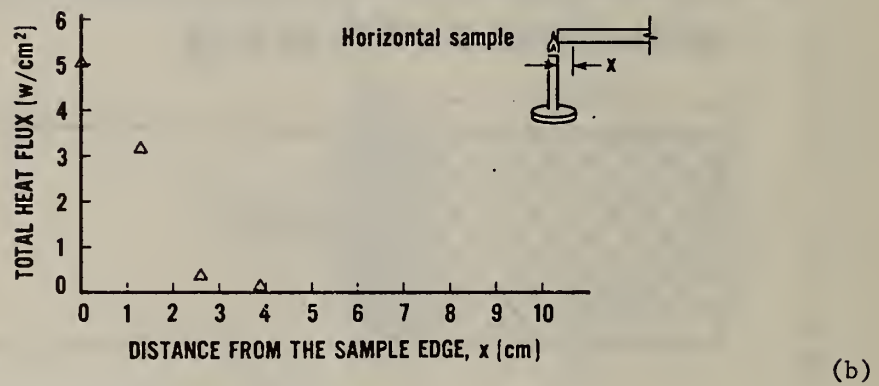
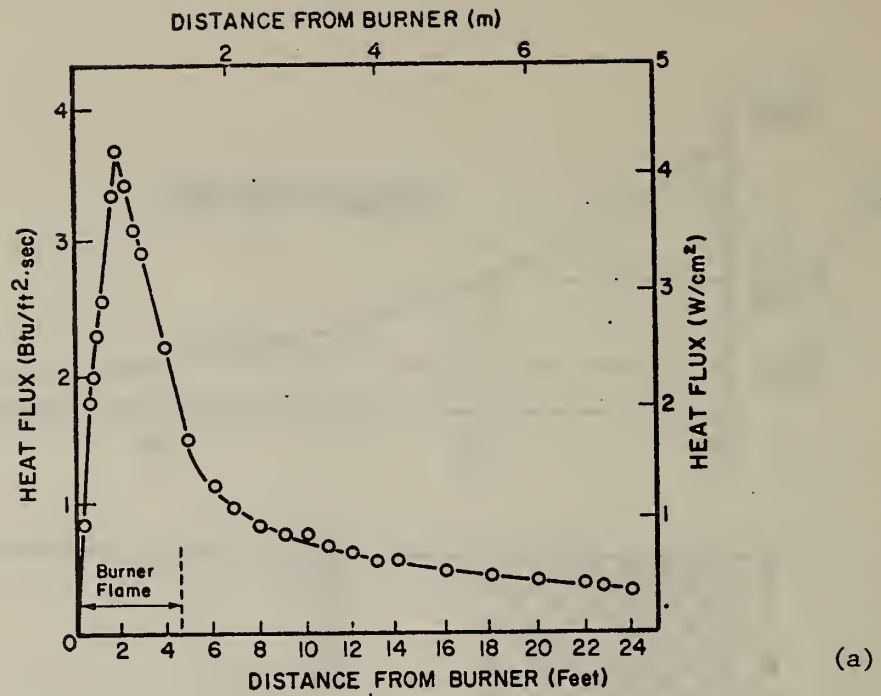


Figure 3 - Igniting Flame Heat Flux for the ASTM E-84 Steiner Tunnel Test (a) and the Bunsen Burner Test, (b,c).

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10. SUPPLEMENTARY NOTES <input type="checkbox"/> Document describes a computer program; SF-185, FIPS Software Summary, is attached.			
11. ABSTRACT <i>(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)</i> The rate of energy release in fire is discussed. The significance of calorimetric measurements of energy release for materials is related to thermal-dynamic parameters, namely heat of reaction and stoichiometric coefficients. It is shown that a common set of parameters is necessary to express ignition, flame spread and mass loss due to combustion and heat transfer in fires. The relationship of ignition and flame spread to rate of energy release in fires is presented along with a presentation on upward spread.			
12. KEY WORDS <i>(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)</i> Calorimeters; correlation; energy transfer; fire tests, flame spread, ignition; mass loss; test methods.			
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